DIODE-PUMPED MICROLASERS INCLUDING RESONATOR MICROCHIPS AND METHODS FOR PRODUCING SAME

Cross-Reference to Related Applications

This application claims the benefit of co-pending U.S. Provisional Patent Application Serial No. 60/504,617 filed on September 22, 2003, claims the benefit of co-pending U.S. Provisional Patent Application Ser. No. 60/505,054 filed on September 24, 2003, and claims the benefit of co-pending U.S. Provisional Patent Application Ser. No. 60/516,454 filed November 3, 2003, the teachings of which applications are fully incorporated herein by reference.

Technical Field

The present invention relates to lasers and more particularly, to high density diode-pumped microlasers including resonator microchips.

Background Information

Microlasers may be used as a replacement for conventional red lasers, particularly red semiconductor diode lasers. While diode lasers can provide wavelength coverage in the blue, red, and near infrared regions, currently no known diode laser technology can produce green wavelengths with any substantial output power. The green wavelength region is particularly important because it is the region where the spectral responsivity of the human eye is at a maximum and where underwater transmission peaks. In addition, diode lasers are generally low-brightness devices with an astigmatic output due to the disparity in divergence angles in the directions parallel and perpendicular to the diode stripe. Although solid state lasers are capable of a higher power output, even compact diode-pumped solid state lasers tend to be too bulky and/or expensive to be used in mass applications.

Furthermore, solid state lasers generally emit their fundamental radiation in the infrared region of the spectrum near and around 1 μm. To convert infrared laser radiation from a solid state laser into the green region, the energy of two infrared photons may be added to form one photon in the green region using a suitable nonlinear optical crystal. This process is known as second-harmonic-generation (SHG). Thus, for the 1064 nm transition in Nd doped YAG or YVO_4 (Orthovanadate) solid state lasers, for

example, frequency-doubling using an appropriate nonlinear optical crystal yields an output wavelength at 532 nm. The nonlinear process referred to as sum-frequency-generation (SFG) can also be applied to a laser transition if a suitable nonlinear optical crystal is available. In addition to SHG and SFG, there are other nonlinear processes that can be used to produce other discrete wavelengths using fixed laser transitions. Some of the more common are third harmonic generation (THG), optical parametric amplification (OPA), and Raman shifting.

Known techniques to generate a variety of wavelengths from solid state lasers across the visible spectrum tend to add bulk and cost to the systems, even when simple diode-pumped designs are utilized. This is particularly true for green lasers designed to run in a single-transverse (Gaussian) mode (STM) and/or single-longitudinal mode (SLM).

Techniques are also known for fabricating compact, frequency converted solid state lasers. According to one method, a laser crystal and a nonlinear optical crystal may be connected and combined by a spacer. However, this type of laser assembly is labor-intensive to produce and relatively expensive. SLM operation was also realized in microchip lasers or microlasers in which a gain medium is disposed between two mirrors to form a cavity. In these microlasers, the cavity length is selected so as to keep the gain bandwidth of the active medium smaller than or equal to the frequency separation of the cavity modes. Although the laser and nonlinear materials are bonded in these microlasers, existing bonding techniques do not allow for joining coated surfaces. Also, the stringent requirements placed on cavity lengths produce lasers that are susceptible to mode hopping noise and are difficult to fabricate efficiently with the desired quantities, production economies and costs.

Alternative techniques to construct a monolithic laser assembly comprising a laser medium and a nonlinear optical crystal include a method of "contact bonding," as used for example, by VLOC, Inc. However, the method of contact bonding individual crystals is still rather expensive, with cost and yield issues. Moreover, only a small fraction of the crystal assembly volume is generally used as a laser and it is therefore difficult to reduce the unit cost.

Other alternate technologies for producing miniaturized lasers operating in the visible regions include frequency-doubled VCSEL (Vertical Cavity Surface Emitting Lasers) structures either externally or internally. Such semiconductor based devices

tend, however, to have limited output power and wavelength capability and also require major investment in production and processing facilities

Accordingly, there is a need for a laser resonator and method capable of producing low-cost, high-density (watts of output power divided by the device volume) microlaser devices, and in particular microlaser devices operating in the green spectral region, for example, near 532 nm.

Brief Description of the Drawings

These and other features and advantages of the present invention will be better understood by reading the following detailed description, taken together with the drawings wherein:

FIG. 1 is a schematic diagram of a diode-pumped microlaser, consistent with one embodiment of the present invention.

FIG. 2 is a schematic diagram of a diode-pumped microlaser, consistent with another embodiment of the present invention.

FIG. 3 is a schematic diagram of a laser resonator microchip for use in a diode-pumped microlaser, consistent with a further embodiment of the present invention.

FIG. 4 is a schematic diagram illustrating one method of making a laser resonator microchip for use in a diode-pumped microlaser, consistent with yet another embodiment of the present invention.

FIG. 5 is a schematic diagram of another embodiment of a laser resonator microchip with an outcoupler having curvature on the inside surface.

FIG. 6 is a schematic diagram of a further embodiment of a laser resonator microchip with an outcoupler having curvature on the outside surface.

FIG. 7 is a schematic diagram of a resonator microchip for use in a passively Q-switched microlaser, consistent with a further embodiment of the present invention.

FIG. 8 is a schematic diagram of a resonator microchip for use in a passively Q-switched eyesafe microlaser, consistent with a further embodiment of the present invention.

FIG. 9 is a schematic diagram of a resonator microchip for use in a passively Q-switched Yb, Er:Glass microlaser, consistent with a further embodiment of the present invention.

FIG. 10 is a schematic diagram of a further embodiment of a resonator microchip having a Nd: YVO_4 crystal assembly to produce third harmonic generation.

Detailed Description

In general, a diode-pumped microlaser consistent with the present invention includes a laser resonator microchip capable of producing an output beam having a wavelength in the green spectral region and having high output power, e.g. in excess of 100mw, with respect to device volume (i.e., a high-density laser device). The term "green spectral region" as used herein shall refer to a region of wavelengths from about 490nm to 570nm. In one embodiment, a microlaser consistent with the invention produces an output wavelength at about 532nm. The laser resonator microchip may include a laser crystal glued to and interferometrically aligned with a nonlinear optical crystal. Although the embodiments shown and described herein produce an output wavelength in the green spectral region, those skilled in the art will recognize that these concepts may be applied to microlasers having other wavelengths.

Referring to FIG. 1, one embodiment of a diode-pumped microlaser 100a includes a laser package 110 having a support structure 112 supporting a laser diode pump source 116 and an extended portion 118 of the support structure 112 supporting a laser resonator microchip 120 in proximity to and in alignment with the laser diode pump source 116. The laser package 110 may also include electrical leads 122 and a hermetically sealed cover 124 with an output window 126. In one embodiment, the laser diode pump source 116 pumps the resonator microchip 120 at a pumping wavelength, and the resonator microchip 120 generates laser light at a fundamental laser wavelength, converts the fundamental wavelength to an output wavelength, and causes an output beam to be emitted at the output wavelength, as will be described in greater detail below.

The laser package 110 may be a modified standard package or a custom package. In one embodiment, the laser package 110 may be based on a standard laser diode package known to those skilled in the art. Examples of such laser diode packages include the 9 mm package, which is circularly symmetric and has a maximum outside diameter of 9 mm, or the 5.4 mm package. Such packages are suitable in terms of minimizing the overall laser volume while providing the functionality for laser operation and the low costs associated with mass applications.

To accept the resonator microchip 120, a standard diode laser package (e.g., a 9 mm package) may be extended, for example, by extruding the pedestal or shelf (i.e., the support structure 112) traditionally used to mount the diode pump source 116 to form a

shelf (i.e., the extended portion 118) on which the resonator microchip 120 is mounted. This allows the diode pump source 116 to be properly aligned along the edge of the support structure 112 (or top shelf) while allowing the center of the resonator microchip 120 to be pumped by the diode pump source 116. In this embodiment, the diode-microchip transfer is achieved by way of a simple butt-coupling of the crystal of the microchip 120 to the output facet of the diode pump source 116.

The cover 124 of the laser package 110 may be welded after diode installation to provide a true hermetic seal. Alternatively, the cover 124 may be glued down to provide a quasi-hermetic seal. The output window 126 may be fabricated from one of many optically transmissive materials, such as sapphire, fused silica, or glass, and may be attached to the cover 124, for example, using a metal to glass sealing technique. The output window 126 may be anti-reflective (AR) coated at the emission wavelength on one or both surfaces. When using a resonator microchip 120 designed for frequency doubling, as will be described below, one or both of the window surfaces may have a coating that is highly reflective (HR) at the fundamental wavelength and/or pumping wavelength and minimizes the amount of light transmitted at any wavelength other than the desired visible wavelength.

The laser diode pump source 116 may be, for example, a diode laser, a fiber-coupled diode, or a diode array. A laser diode pump source 116 having an output power of 1 W or less may be used to minimize difficulties in removing the heat, although the 9 mm package may be appropriate for running diodes up to 2 W output power or more. One type of 9 mm package may be fabricated using a Cu/W alloy and may have three electrical leads 122, two that are isolated from the package body by using metal to glass seals, and a third lead (not shown in FIG. 1) that provides a ground for the body.

According to one method of fabrication, the resonator microchip 120 is placed on the extended portion 118 and may be aligned using a precision alignment system known to those skilled in the art. A small drop of optical glue or cement (e.g., UV curable optical cement) may be applied to the extended portion 118 before the resonator microchip 120 is placed on it, to ensure that the resonator microchip 120 will be stably affixed. Once alignment is achieved, the optical cement is hardened (e.g., using a UV lamp) and the microchip laser is then precisely aligned. For good laser efficiency, the air gap between the diode pump source 116 and the resonator microchip 120 may be minimized, and in one embodiment, is less than1 μm thick.

According to another embodiment shown in FIG. 2, a microlaser 100b may also include a discrete outcoupler 130 supported on the extended portion 118. In this embodiment, both the outcoupler 130 and the resonator microchip 120 may be picked and placed using a precision alignment system and glued down to the shelf, for example, using a UV curable optical glue or cement. The microlaser 100b may include the same laser package (e.g., a 9 mm package) and arrangement as described above.

The microlaser 100a including the resonator microchip 120 described above is capable of producing in excess of 100mW of output power in the green spectral region with good alignment and high reliability characteristics. The microlaser 100b including discrete outcoupler 130 in addition to the resonator microchip 120 enables even higher output powers with reliable alignment and stable operation.

According to variations of the microlasers 100a, 100b, the diode pump source 116 may be either butt-coupled or direct-coupled, and the pump assembly may or may not include a short multimode fiber to symmetrize the astigmatic diode beam. The laser package 110 may also be modified to house only the resonator microchip 120, while the diode pump light is introduced using a fiber source. In addition, the diode pump source 116 may or may not include a fast-axis collimating (FAC) lens, or a slow axis collimating lens or both. Lensing of the diode pump source 116 may produce equal divergence or collimated output. The use of diodes designed to have low divergence increases the conversion and overall efficiencies. The laser package 110 may also contain a photodiode to provide feedback to an external electrical laser controller for the purpose of providing constant power output.

The laser package 110 may also be placed on an external cooler, such as a TEC, to provide a constant operating temperature to the entire assembly. Nearly noise-free green lasers can be produced in this manner by temperature tuning the TEC to achieve SLM output. Lasers operating at the fundamental frequency can also be frequency tuned by using the same technique. Cooling may also be provided by a cryogenic cooling system, including for example, cryogenic dewars, or cold fingers, or closed cycle Gifford-McMahon or Stirling coolers. For certain materials, such as Yb:YAG, for example, which operates on a quasi-three-level fundamental transition at room temperature, more efficient four-level operation may be achieved at low temperatures. In order to control temperature, a thermistor or other miniature temperature sensing device can be placed either externally on or internal to the laser package 110. A miniature

piezoelectric translator (PZT) may also be incorporated in the package 110 for the purpose of enforcing a laser output polarization or frequency tuning. These and other techniques known to those skilled in the art for providing for temperature control and/or stabilization of the packaged microlaser assemblies may be implemented in the microlaser.

Referring to FIG. 3, one embodiment of the resonator microchip 120 is described in greater detail. The resonator microchip 120 may include a laser crystal 140 and a nonlinear optical crystal 150 glued together. In one embodiment, the laser crystal 140 is Nd:YVO_4 and the nonlinear optical crystal 150 is Type II KTP. The laser crystal 140 may also be made of other laser crystal materials including, but not limited to, Nd:YAG, Nd:YALO, and Nd: YLF. The nonlinear optical crystal 150 may also be made of other nonlinear optical crystal materials including, but not limited to, $LiNbO_3$. The crystals 140, 150 may be fabricated in different geometries, for example, as plates or as rods.

In general, the resonator microchip 120 is optically pumped by radiation (e.g., from the laser diode pump source 116) at a pump wavelength and laser light at a fundamental laser wavelength is optically trapped inside the resonator microchip 120. In one embodiment, the nonlinear optical crystal 150 provides frequency-doubling of the laser light at the fundamental wavelength to produce an output beam at the output wavelength. The inside surfaces and outside surfaces of the crystals 140, 150 may be coated to be highly reflective (HR), highly transmissive (HT), or anti-reflective (AR) at various wavelengths, as is known to those skilled in the art. Although this embodiment of the resonator microchip uses intracavity frequency doubling, the microlaser described herein may also implement other lasing and frequency conversion techniques known to those skilled in the art.

The internal surface of the laser crystal 140 and the nonlinear optical crystal 150 may be glued together using a layer of optical glue 160, such as an ultraviolet (UV) curable glue that is robust and has low absorption at the lasing and pump wavelengths. Suitable optical glues are available from Norland Products, Inc., of New Brunswick, NJ. Gluing the surfaces together, as opposed to contact bonding, enables less expensive mass-production of green and other visible miniaturized lasers.

Although the glue 160 may be applied directly to the laser crystal 140 and nonlinear optical crystal 150, there may be some disadvantages. Some glues have an index of refraction in the range of 1.45-1.6. Because of the index difference between the

glue and $Nd:YVO_4$ (about 2.03, using the average of three crystalline axes) and the KTP (index averaged over the three crystalline axes of about 1.77), for example, there may be a finite loss encountered at each glue-dielectric interface. These losses can be detrimental to the efficiency and intensity of the fundamental beam.

To obtain higher performance, anti-reflective (AR) dielectric coatings 170, 172 may be applied to the internal faces of the laser crystal 140 and the nonlinear optical crystal 150. The dielectric coatings 170, 172 are in contact with the dielectric crystal (e.g., $Nd:YVO_4$ or KTP) on one side and the glue 160 on the other side. Using the dielectric coatings 170, 172, the resonator assembly losses may be lowered to levels comparable to the more complicated contact-bonding assembly procedures.

In one embodiment, the resonator microchip 120 may be designed to produce an output beam having an output wavelength in the green spectral region. The outside surface 142 of the laser crystal 140 may be coated to be highly reflective at a fundamental laser wavelength (e.g., 1064 nm) and at the output wavelength (e.g., 532 nm) and highly transmissive at a pump wavelength (e.g., 808 nm). The outside surface 152 of the nonlinear optical crystal 150 is coated to be reflective at the fundamental laser wavelength (e.g., 1064 nm) and transmissive at the output wavelength (e.g., 532 nm), which is in the green spectral region. The dielectric coatings 170, 172 may be anti-reflective at the fundamental and output wavelengths (e.g., 1064 nm and 532 nm).

According to one specific example, the laser resonator microchip 120 may include plates of $Nd:YVO_4$ and KTP oriented for Type II phase-matching glued together using a Norland UV curable glue against uncoated crystal surfaces. The laser resonator microchip 120 may have a size of about 1 mm x 2 mm. The laser diode pump source 116 may be a 1 W 808 nm fibered (0.22 NA, 100 μm core) laser diode butt-coupled to the microchip 120. The resulting microlaser is capable of producing 20 mW of green output at 532 nm with ~ 200 mW of diode pump power.

When un-optimized dielectric coatings 170, 172 on the laser crystal 140 and the nonlinear optical crystal 150 are used in contact with the adjacent glue layer 160, the resulting microlaser is capable of producing up to 80 mW. Both of these examples of a microlaser are capable of producing an output beam that is both STM and SLM and are capable of being maintained by temperature tuning the microchip with a thermoelectric cooler (TEC). Using optimized dielectric coatings on the laser crystal 140 and the nonlinear optical crystal 150, the resulting microlaser may be capable of producing 100-

200 mW of green output power. Thus, embodiments of the microlaser described herein may approach power levels demonstrated with the standard VLOC contact-bonded assemblies but using the high density low cost fabrication techniques.

The resonator microchip 120 may be fabricated so that the two outside resonator surfaces 142, 152 are parallel to one another. According to one method of alignment, a first dielectric plate of either laser crystal material or nonlinear optical crystal material may be anchored in place and a small amount of glue may be applied to the anchored plate, for example, in the center. The second dielectric plate may then be placed on top of the first, causing the glue to spread out to form a thin uniform layer of glue. A monochromatic light source may be used to expose the plates to light while manipulating or rocking the top plate in a predetermined way to wash out the fringes formed by the monochromatic light. When the fringes disappear, the resonator is considered to be interferometrically aligned and the glue is at least partially hardened, for example, by exposing UV curable glue to ultraviolet (UV) light.

According to one method of mass producing resonator microchips, as shown in FIG. 4, large wafers of the laser crystal 140 material and the nonlinear optical crystal 150 material may be glued together to form a bonded wafer assembly 200. The bonded wafer assembly 200 may be interferometrically aligned and glued using the techniques described above. The bonded wafer assembly 200 may then be cut into numerous laser resonator microchips 120. The bonded wafer assembly 200 may be cut, for example, along lines 210 using a dicing saw or other dicing techniques known to those skilled in the art. The resonator 120 microchips may be cut with a size of about 1 mm x 2 mm or smaller depending upon the dicing technique. Using wafers that are precisely flat and parallel enables substantially the entire bonded wafer assembly 200 to be used to produce numerous efficient resonator microchips 120.

Using this bonding and dicing process avoids having to separately bond surfaces of the individual crystals, allowing the cost per laser device to be reduced. The use of UV curable optical glue advantageously prevents debonding during the dicing process. Also, the method described above allows the crystalline materials to be used sparingly, with nearly the entire original wafer surface utilized for a large number of laser resonator microchips. Furthermore, the resonator microchips fabricated according to the methods described above lend themselves to usage in miniature packages, which can be highly efficient. Also, the methods described above allow the dimensions of the crystals to be

selected to facilitate STM and/or SLM operation while allowing greater flexibility in providing output at a larger variety of wavelengths through appropriate choices of coatings and crystals.

Referring to FIGS. 5 and 6, an outcoupler 130a, 130b may be placed adjacent to or in contact with an output face of a resonator microchip 120 to construct a flat/curved laser resonator. The outcoupler 130a, 130b introduces some curvature into the resonator to assure stability, particularly at higher output powers. In particular, when the 532 nm output beam out of a bonded crystal assembly or resonator microchip exceeds about 30 mW, alignment of the crystal assembly becomes sensitive and difficult to maintain. For powers greater than about 30 mW, the outcoupler may be used to maintain alignment stability and STM output, allowing the microchip assembly to produce much higher green output power with good beam-quality.

In one embodiment (FIG. 5), the outcoupler 130a has a finite curvature on an inside surface 132. The magnitude of the curvature and the proximity of the outcoupler 130a to the resonator microchip 120 may be selected to provide stability to the resonator microchip, for example, using standard optical design methods known to those skilled in the art. The inside surface 132 of the outcoupler 130a may be coated to be highly reflective at the fundamental laser wavelength (e.g., 1064 nm) and highly transmissive at the output wavelength (e.g., 532 nm) and the outside surface 134 of the outcoupler 130a may be coated to be anti-reflective at the output wavelength (e.g., 532 nm). In this embodiment, the outside or output surface 152 of the nonlinear optical crystal 150 may be anti-reflective coated at both the fundamental laser wavelength (e.g., 1064 nm) and at the output wavelength (e.g., 532 nm). The inside surface of the nonlinear optical crystal 150 and the surfaces of the laser crystal 140 may be configured, for example, with the reflection and transmission characteristics described above.

In another embodiment (FIG. 6), an outcoupler 130b may have curvature on the outside surface 134 and may be flat on the inside surface 132. This configuration allows the inside surface of the outcoupler 130b to be glued to the resonator microchip 120 forming a three plate sandwich structure. The outside surface 152 of the nonlinear optical crystal 150 and the inside surface 132 of the outcoupler 130b may be glued together using, e.g., the UV curable glue discussed above. The surfaces 152, 132 of the nonlinear optical crystal 150 and the outcoupler 130b may be dielectric coated to minimize the reflective loss. In this embodiment, the inside surface 132 of the

outcoupler 130b and the outside surface of the nonlinear optical crystal 150 may be anti-reflective coated at the fundamental laser wavelength (e.g., 1064 nm) and at the output wavelength (e.g., 532 nm) and the outside surface of the outcoupler 130b may be highly-reflective at the fundamental wavelength (e.g., 1064 nm) and highly transmissive at the output wavelength (e.g., 532 nm). The inside surface of the nonlinear optical crystal 150 and the surfaces of the laser crystal 140 may be configured, for example, with the reflection and transmission characteristics described above.

The resonator microchip structures described above can be used to produce continuous wave (CW) output from fundamental and frequency-doubled laser transitions using simple flat/flat or flat/curved resonators based on the well-known laser transitions in materials like Nd:YAG, Nd:YVO_4, Nd:YALO, Nd:YLF, and nonlinear crystals such as KTP or $LiNbO_3$. The high density microchip fabrication techniques described herein may also be extended to produce more complicated microchips operating at other wavelengths and alternative operating modes. Some of these alternative implementations are discussed below.

In particular, the methods described herein may be used to create resonator configurations operating on any number of alternative laser transitions, depending on the application. Table 1 lists some of the transitions utilized in Nd-doped laser materials. SHG frequency doubling can also be applied to any laser transition if a suitable nonlinear crystal can be identified that will phase match to provide SHG output. Alternatively, two laser transitions can be combined intracavity to provide SFG output, thus further increasing the range of wavelengths that may be produced with intracavity conversion. In one particular example, SFG of the 1318.7 nm and 946 nm transitions in Nd:YAG may be used to produce output at 550.84 nm.

Table 1: Fundamental and Second Harmonic Wavelengths for Various Laser Crystals

-Laser Transitions Assumed Operating Near 300 °K

Material/Transition	Fundamental Wavelength (nm)	SHG Wavelength (nm)
Nd:YAG		
$^4F_{3/2}$-$^4I_{13/2}$	1318.70	659.35
$^4F_{3/2}$-$^4I_{11/2}$	1064.20	532.10
$^4F_{3/2}$-$^4I_{9/2}$	946.00	473.00
Nd:YVO$_4$		
$^4F_{3/2}$-$^4I_{13/2}$	1341.92	670.96
$^4F_{3/2}$-$^4I_{11/2}$	1064.28	532.14
$^4F_{3/2}$-$^4I_{9/2}$	915.25	457.63
Nd:YALO		
$^4F_{3/2}$-$^4I_{13/2}$	1341.40	670.70
$^4F_{3/2}$-$^4I_{11/2}$	1079.50	539.75
$^4F_{3/2}$-$^4I_{9/2}$	870.00	435.00
Nd:YLF		
$^4F_{3/2}$-$^4I_{13/2}$	1313.00	656.50
$^4F_{3/2}$-$^4I_{11/2}$	1053.00	526.50
$^4F_{3/2}$-$^4I_{11/2}$	1047.00	523.50
$^4F_{3/2}$-$^4I_{9/2}$	908.27	454.13
$^4F_{3/2}$-$^4I_{9/2}$	903.50	451.75
Yb:YAG		
$^2F_{5/2}$-$^2F_{7/2}$	1029.30	514.65

In other alternative embodiments, the temporal format of the output may be changed from the CW format discussed above. In one alternative embodiment, for example, the laser diode source can be modulated, that is - turned on and off in some format so as to produce laser output proportional to the laser diode power. For 100 %

laser diode modulation, the laser diode pump can simply be turned off and on to produce long-pulse or free-running output at a prescribed repetition rate. Alternatively, the resonator microchip can be Q-switched using, for example, a saturable absorber. The saturable absorber can be doped into the lasing crystal itself (self-Q-switching) or into a separate crystal.

According to one embodiment, shown in FIG. 7, a resonator microchip 300 may be designed for use in a passively Q-switched microlaser. The resonator microchip may include a laser material 310 such as $Nd:YVO_4$ and a nonlinear optical crystal 320 made of a passive Q-switching material such as Cr^{4+}:YAG. In this embodiment, the $Nd:YVO_4$ crystal may be pumped by a diode source that is CW or pulsed (modulated). The inside surface of the laser crystal 310 may be HR coated at 1064 nm and HT coated at 808 nm. The nonlinear optical crystal 320 may have a partially reflecting coating at 1064 nm applied to its outside surface, and an anti-reflective coating at 1064nm may be applied at the interface between the laser material 310 and the nonlinear optical crystal 320. As described above, the interface between the two crystals 310, 320 may have a UV curable optical glue and the surfaces in contact with the glue may be dielectric-coated to minimize reflective losses. This embodiment of the resonator microchip 300 may also be fabricated using the methods described above.

This embodiment of the resonator microchip may be used to produce microjoule level pulse energies (typically 3-10 μJ) at kHz repetition rates from miniaturized low cost devices. To achieve this performance in one example, a pulsed laser diode pump source may be utilized with a pump duration comparable to or shorter than the fluorescence decay time for the $Nd:YVO_4$ crystal (typically ~ 100 μsec). Such diode lasers are readily available from several commercial vendors. Microlasers made according to this embodiment exhibit no apparent degradation to the glue layer or coatings with pulsed laser diode pump source intensities above 250 MW/cm^2 sustained for over 10^9 shots.

In further alternatives with some materials like Nd:YAG, Cr^{4+} can, for example, be co-doped with the active Nd ion. In this case, a single plate may be formed, which can be diced and made into microchips, lowering the overall cost of fabrication.

According to another embodiment, as shown in FIG. 8, a resonator microchip 330 may be designed for use in a Q-Switched laser resonator providing an alternative wavelength, such as an eye-safe laser operating at or near 1.54 μm. This resonator microchip 330 is similar to that shown in FIG. 7 with an optical parameter oscillator

(OPO) device 332 including an appropriately coated KTP or KTA crystal. Thus, this microchip laser includes three separate layers 310, 320, 332 glued together, for example, a Nd:YVO_4 crystal, a Cr^{4+}:YAG Q-switch, and a KTP or KTA nonlinear crystal phase-matched to the 1064 nm transition in Nd:YVO_4 to produce output near 1540 nm. The KTP/KTA crystal OPO device 332 may be coated on an inside surface to be highly reflective at 1540 nm and anti-reflective at 1064 nm and coated on an outside surface to be highly reflective at 1064 nm and partially reflective at 1540. The OPO device 332 may be flat on the outside surface or may be curved to provide resonator stability and allow operation in STM. The outside surface of the layer 310 may be coated to be highly reflective at 1064nm and highly transmissive at 808nm, and the interface between layers 310 and 320 may include an anti-reflective coating at 1064nm. This laser microchip 330 may be longer than the devices shown previously because the nonlinear coefficient for 1.54 μm generation is small and as much as 1-2 cm of the OPO crystal length may be required to produce good efficiency. This embodiment of the resonator microchip 330 may also be fabricated using the methods described herein.

According to a further embodiment, shown in FIG. 9, a resonator microchip 340 may include a Yb,Er:Glass laser material 350 designed for a laser operating at 1540 nm, which is Q-switched with Co^{2+}: Spinel crystal 360 or some other appropriate material. In this embodiment, the Yb absorption band may be pumped by a diode operating near 940 nm followed by energy transfer to the Er ion which lases at 1540 nm. The Yb,Er:Glass laser material 350 may be coated on an outside surface to be highly reflective at 1540 nm and highly transmissive at 940 nm and coated on an inside surface to be anti-reflective at 1540 nm and highly reflective at 940 nm. The outside surface of the Co^{2+}: Spinel crystal 360 may be either curved or flat and may be coated to be partially reflective at 1540 nm. The crystals 350, 360 may be glued as described above. Because the crystal thicknesses can be minimized, this type of a pulsed eye safe laser is amenable to mass production by dicing large glued wafers into numerous small assemblies.

According to a further embodiment, shown in FIG. 10, a resonator microchip 370 may also be capable of producing third or fourth harmonic light in either CW or pulsed modes. For example, the resonator microchip 370 may be similar to those described above having a Nd:YVO_4 laser crystal 140 and a nonlinear optical KTP crystal 150 with an additional nonlinear optical crystal 372 (e.g., BBO or LBO). The additional nonlinear optical crystal 372 is used to produce third harmonic output, for example, at 355 nm in

the ultraviolet or blue spectral region by tripling the 1064 nm transition of Nd:YAG or Nd:YVO_4. The additional nonlinear optical crystal 372 may be coated on an inside surface to be anti-reflective at 1064 nm and at 532 nm and highly reflective at 355 nm and coated on an outside surface to be highly reflective at 1064 nm and 532 nm and highly transmissive at 355 nm. The outside surface of the additional nonlinear optical crystal 372 may also be curved or flat.

Other embodiments may be fabricated using solid-state Raman converters and to produce multiple wavelengths. For example, a solid-state Raman material may be glued to a Nd:YVO_4 crystal, both with the appropriate dielectric coatings. This type of device may produce output that is Raman shifted into the infrared from the primary transition at 1064 nm.

In yet another embodiment, more than one wavelength can be provided simultaneously from a single resonator microchip. For example, using appropriate coatings, a crystal assembly such as that shown in FIG. 3 can be designed that will simultaneously produce output at 1064 nm and 532 nm.

Further variations of the concepts described above are also possible. Those skilled in the art will recognize that a different resonator, operating mode, laser materials, Q-switches or method of Q-switching, nonlinear crystals, coatings or combinations of coatings may be used. Those skilled in the art will also recognize that other methods of gluing the crystals together (e.g., using something other than Norland glue) may also be used.

In summary, according to one method of producing a laser resonator microchip, a laser crystal wafer and a nonlinear optical crystal wafer are provided and inside surfaces of the wafers are glued using a UV curable glue to form a bonded wafer assembly. The wafers may also be interferometrically aligned before the glue hardens. The bonded wafer assembly is diced to form at least one laser resonator microchip.

According to one method of making a diode-pumped laser, the laser resonator microchip is packaged in a diode laser package such that the laser resonator microchip is aligned with a laser diode.

One embodiment of a laser resonator microchip includes a laser crystal, a first anti-reflective dielectric coating on an inside surface of the laser crystal, a nonlinear optical crystal, a second anti-reflective dielectric coating on an inside surface of said nonlinear optical crystal, and a layer of UV cured optical glue between the dielectric

coatings. The laser crystal and nonlinear optical crystal are glued and interferometrically aligned. The dielectric coatings are anti-reflective at a fundamental wavelength and at an output wavelength.

One embodiment of a diode-pumped microlaser includes a laser diode package, a laser diode mounted on a support structure in the laser diode package, and a laser resonator microchip mounted on an extended portion of the support structure in the laser diode package. The laser resonator microchip is aligned with the laser diode and configured to produce laser light having a wavelength in the green spectral region. The laser resonator microchip includes a laser crystal and a nonlinear optical crystal glued to and interferometrically aligned with the laser crystal.

While the principles of the invention have been described herein, it is to be understood by those skilled in the art that this description is made only by way of example and not as a limitation as to the scope of the invention. Other embodiments are contemplated within the scope of the present invention in addition to the exemplary embodiments shown and described herein. Modifications and substitutions by one of ordinary skill in the art are considered to be within the scope of the present invention, which is not to be limited except by the following claims.